B to charmonium - mini-summary

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1 Introduction

I summarize recent experimental results on B to charmonium decays. Decays of B meson to final states that include charmonium states play an important role in the study of CP violation at B-factories. The decay modes $B_{CP} \to J/\psi K_S$, $\psi(2S)K_S$, $\chi_{c1}K_S$, $\eta_c K_S$, $J/\psi K_L$ and $J/\psi K^{*0}(K^{*0} \to K_S\pi^0)$ have been used for $\sin 2\phi_1$ measurements [1] [2] [3] [4] [5]. These two-body decay modes are dominated by the color suppressed $b \to c$ transition. Other CP eigenstates of the neutral B meson, e.g. $J/\psi\rho^0$, may also be useful for the CP measurements. Meanwhile, the branching fractions for the $B \to$ *charmonium* decays can provide valuable information on their decay mechanism.

2 Non-factorizable decay modes

In the factorization approximation, the production of χ_{c0} and χ_{c2} are not allowed by angular momentum and vector-current conservation. However, these decays can occur if factorization is broken by an exchange of soft gluons between the quarks.

2.1 Observation of $B^+ \to \chi_{c0}K^+$

Using a data sample containing 31.3 million $B\overline{B}$ events collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric e^+e^- collider, the Belle collaboration has made the first observation of $B^+ \to \chi_{c0}K^+$ [6].

The χ_{c0} candidates are reconstructed from $\chi_{c0} \to \pi^+\pi^-$ and K^+K^-. Two kinematic variables, the beam-constrained mass, $M_{\rm bc} = \sqrt{E^2_{\rm beam} - \vec{P}^2_{\rm recon}}$, and energy difference $\Delta E = E_{\rm recon} - E_{\rm beam}$ in the $\Upsilon(4S)$ center of mass frame, are formed to isolate the signal. Here $E_{\rm beam}$, $E_{\rm recon}$ and $\vec{P}_{\rm recon}$ are the beam energy, the reconstructed energy, and the reconstructed momentum of the signal candidate, respectively. Figure 1 shows the invariant masses of $\pi^+\pi^-$ and K^+K^-. The peaks near 3.4 GeV/c^2 are identified as the χ_{c0} meson. The peak position in the K^+K^- spectrum

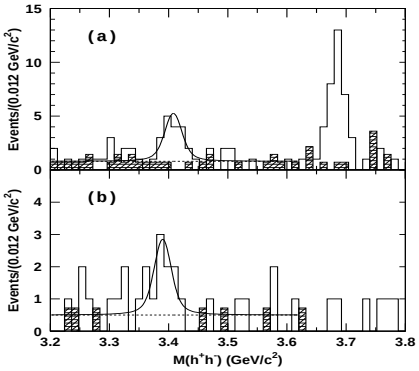

Figure 1: The (a) $\pi^+\pi^-$ and (b) K^+K^- invariant mass spectra. Open histograms correspond to events from the B signal region, and hatched histograms correspond to events from the ΔE sidebands. The curves are results of fits [6].

is shifted. This could be explained by the interference of $B^+ \to \chi_{c0}K^+$ with the non-resonant $B^+ \to K^+K^+K^-$. The peak at 3.69 GeV/c^2 in the $\pi^+\pi^-$ spectrum is due to $B^+ \to \psi(2S)K^+$, $\psi(2S) \to \mu^+\mu^-$ with the muons misidentified as pions.

Using the $\chi_{c0} \to \pi^+\pi^-$ decay channel, the ratio of branching fractions is found to be:

$$\frac{\mathcal{B}(B^+ \to \chi_{c0}K^+)}{\mathcal{B}(B^+ \to J/\psi K^+)} = 0.60^{+0.21}_{-0.18} \pm 0.05 \pm 0.08,$$

where the first error is statistical, the second is systematic, and the third is due to the uncertainty in the branching fraction for $\chi_{c0} \to \pi^+\pi^-$. The branching fraction is measured to be

$$\mathcal{B}(B^+ \to \chi_{c0}K^+) = (6.0^{+2.1}_{-1.8} \pm 1.1) \times 10^{-4},$$

which is comparable to those for $B^+ \to J/\psi K^+$ and $B^+ \to \chi_{c1}K^+$ decays. The $\chi_{c0} \to K^{*0}K^-\pi^+$ decay channel has been also studied and the results are in good agreement with those determined from $\chi_{c0} \to \pi^+\pi^-$. The statistical significance of the signal is 6σ when these two channels are combined. This measurement indicates a significant non-factorizable contribution in B to charmonium decays.

2.2 Observation of $B \to \chi_{c2}X$

The Belle collaboration has also observed χ_{c2} production in B-meson decay [7]. The analysis is based on a data sample containing 31.9 million $B\overline{B}$ events collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric e^+e^- collider.

The χ_{c2} candidates are reconstructed via $J/\psi\gamma$, $J/\psi \to l^+l^-$. The photon energy resolution is studied using $D^{*0} \to D^0\gamma$ decay. The σ_E/E_γ is $(2.61 \pm 0.04)\%$ around

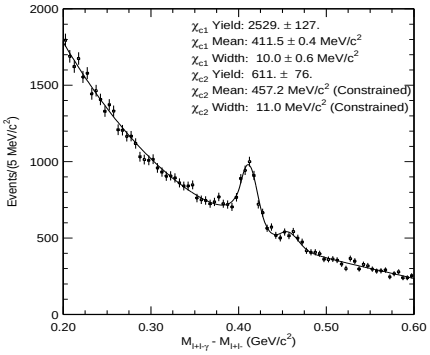

Figure 2: The distribution of the mass difference between the χ_c and the J/ψ candidates events [7].

400 MeV. The good photon energy resolution leads to a clear separation between the χ_{c2} peak and the larger χ_{c1} peak as shown in Fig. 2. To extract signal yields, the distribution is fit to two Crystal Ball line shapes and a third-order Chebyshev polynomial for the background. The continuum subtracted yield for $B \to \chi_{c2}$ is 607^{+76}_{-94} events and the branching fraction for $B \to \chi_{c2}X$ is $(1.80^{+0.23}_{-0.28} \pm 0.26) \times 10^{-3}$. The branching fraction for $B \to \chi_{c1}X$ is also measured. The momentum spectrum of χ_{c2} does not show a significant contribution from two body $B \to \chi_{c2}K$, in contrast to the momentum spectrum for $B \to \chi_{c1}$.

3 Other exclusive decay modes

3.1 $B^0 \to J/\psi\pi^+\pi^-$

The BaBar collaboration has measured the branching fraction for the $B \to J/\psi\pi^+\pi^-$ decay [8]. The data set contains approximately 56 million $B\overline{B}$ pairs produced at the $\Upsilon(4S)$ resonance with the BaBar detector at the PEP-II asymmetric e^+e^- collider. The $B \to J/\psi\pi^+\pi^-$ decay mode includes $J/\psi\rho^0$ and the non-resonant $J/\psi\pi^+\pi^-$ components. The invariant mass of the two pions, $M(\pi^+\pi^-)$, is plotted in Fig. 3. The signal yield is obtained by an unbinned maximum likelihood fit performed on the invariant mass distribution. The branching fraction for $B^0 \to J/\psi\pi^+\pi^-$ is measured to be $(5.0 \pm 0.7 \pm 0.6) \times 10^{-5}$. It is about 20 times smaller than the branching fraction for $B^0 \to J/\psi K^0$ because of the Cabibbo suppression of $B \to J/\psi\pi^+\pi^-$.

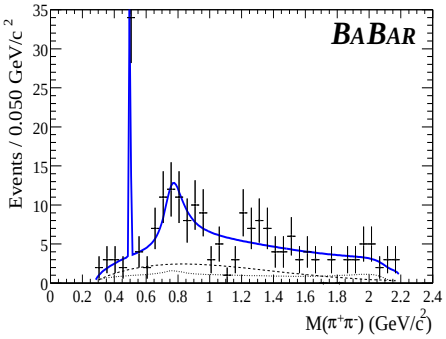

Figure 3: Distribution of the invariant mass M($\pi^+\pi^-$) for the B candidates. The solid line is the result of the unbinned likelihood fit. The dotted (dashed) line represents the background from non-J/ψ (inclusive-J/ψ) events. [8].

3.2 $B \to J/\psi K^*$

The $J/\psi K^*$ system has three helicity states and hence is a mixture of the CP-even and CP-odd eigenstates. The full angular analysis can determine the CP mix, which must be known to measure sin2ϕ_1 when the decay $B^0 \to J/\psi K^{*0}$, $K^{*0} \to K_S\pi^0$ is used. The angular analysis also provides a test of the validity of the factorization hypothesis for B meson decays to charmonium.

The branching fractions for $B^+ \to J/\psi K^{*+}$ and $B^0 \to J/\psi K^{*0}$, where $K^{*+} \to K^+\pi^0$, $K_S\pi^+$ and $K^{*0} \to K^+\pi^-$,$K_S\pi^0$, are listed in Table 1 for comparison [9] [10]. The results are all in good agreement. Figure 4 also shows evidence for the decay $B^0 \to J/\psi K_2^{*0}(1430)$. Some excess is observed in the region between 1.1 GeV/c^2 to 1.3 GeV/c^2 in these measurements. Its source is not fully understood.

The decay amplitudes of $B \to J/\psi K^*$ are measured in the transversity frame [11] by fitting the angular distributions in Fig. 5. The results from various experiments are compared in Table 2 [9] [12] [10]. They are consistent. The value of $|A_\perp|^2$, which corresponds to the CP-odd eigenstate, shows that CP-even component dominates in the $B^0 \to J/\psi K^{*0}$, $K^{*0} \to K_S\pi^0$ decay. The parameter $arg(A_\parallel)$ should be 0 or π in the factorization limit. It is shifted from π in all four measurements. However, the shift is not yet statistically significant enough to draw a conclusion.

3.3 $B \to \eta_c K^{(*)}$

The decay $B \to \eta_c K$ has the same quark level diagram as $B \to J/\psi K$. However, unlike J/ψ, η_c decays hadronically rather than leptonically with rates of a few percent or less for each channel. The decay modes $B^0 \to \eta_c K^0$, $\eta_c \to K_S^0 K^-\pi^+$ and $K^+K^-\pi^0$ have been used to measure sin2ϕ_1. Other decay channels of the η_c may also be useful

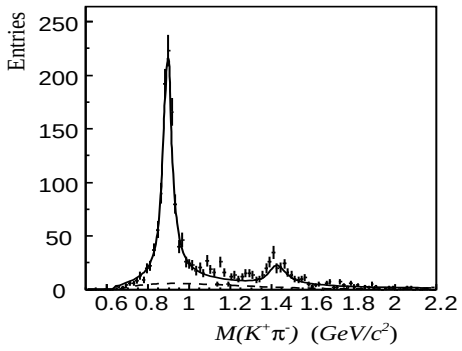

Figure 4: The $K^+\pi^-$ invariant mass distribution from Belle. The solid line is a fit to two Breit-Wigner functions corresponding to $K^*(892)$ and $K_2^*(1430)$ with a background function (dashed line).

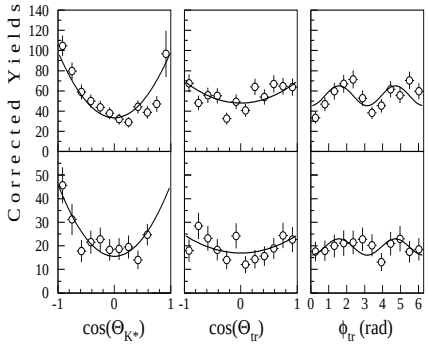

Figure 5: The background-subtracted angular distributions for the channels without (top) and without (bottom) a π^0. The curves correspond to the fit [10].

for future CP measurements.

BaBar has measured the branching fractions of $B^+ \to \eta_c K^+$ and $B^0 \to \eta_c K^0$ [13] using a data sample containing 22.7 million $B\overline{B}$ pairs. The η_c is reconstructed in the decay modes: $K_S^0 K^-\pi^+$, $K^+K^-\pi^0$, and $2(K^+K^-)$. They observed statistically significant B meson signals in the $K_S^0 K^-\pi^+$ and $K^+K^-\pi^0$ channels. They also observed exclusive η_c signals.

Belle has measured the branching fraction of $B^+ \to \eta_c K^+$ and $B^0 \to \eta_c K^0$ using a data sample containing 31.3 million $B\overline{B}$ pairs. The η_c is reconstructed in the decay modes: $K_S^0 K^-\pi^+$, $K^+K^-\pi^0$, $K^{*0}K^-\pi^+$ and $p\overline{p}$. We observed statistically significant B meson signals in $K_S^0 K^-\pi^+$, $K^+K^-\pi^0$, $K^{*0}K^-\pi^+$ and in the $p\overline{p}$ channel. Figure 6 shows the invariant mass of η_c for events in the M_{bc} and ΔE signal region. Fitting to a Breit-Wigner convolved with the resolution determined from MC, we find a intrinsic

Experiment	$\mathcal{B}(B^0 \to J/\psi K^{*0})$ $(\times 10^{-3})$	$\mathcal{B}(B^+ \to J/\psi K^{*+})$ $(\times 10^{-3})$
CLEO	$1.32 \pm 0.15 \pm 0.17$	$1.41 \pm 0.20 \pm 0.24$
BaBar	$1.24 \pm 0.05 \pm 0.09$	$1.37 \pm 0.09 \pm 0.11$
Belle	$1.29 \pm 0.05 \pm 0.13$	$1.28 \pm 0.07 \pm 0.14$

Table 1: The measured branching fractions for $B^+ \to J/\psi K^{*+}$ and $B^0 \to J/\psi K^{*0}$.

Exp.	$\lvert A_0\rvert^2$	$\lvert A_\perp\rvert^2$	$arg(A_\parallel)$ (rad)	$arg(A_\perp)$ (rad)
CLEO	$0.52 \pm 0.07 \pm 0.04$	$0.16 \pm 0.08 \pm 0.04$	$3.00 \pm 0.37 \pm 0.04$	$-0.11 \pm 0.46 \pm 0.03$
CDF	$0.59 \pm 0.06 \pm 0.01$	$0.13^{+0.12}_{-0.09} \pm 0.06$	$2.2 \pm 0.5 \pm 0.1$	$-0.6 \pm 0.5 \pm 0.1$
BaBar	$0.60 \pm 0.03 \pm 0.02$	$0.16 \pm 0.03 \pm 0.01$	$2.50 \pm 0.20 \pm 0.08$	$-0.17 \pm 0.16 \pm 0.07$
Belle	$0.62 \pm 0.02 \pm 0.03$	$0.19 \pm 0.02 \pm 0.03$	$2.83 \pm 0.19 \pm 0.08$	$-0.09 \pm 0.13 \pm 0.06$

Table 2: The decay amplitudes in $B \to J/\psi K^*$. The first errors are statistical and the second systematic.

width $\Gamma(\eta_c) = 29 \pm 8$ MeV and a mass of $M(\eta_c) = 2979.6 \pm 2.3$ MeV. The errors are statistical only. The results are consistent with world averages [14] and the CLEO result [15].

The B branching fractions are quoted for the $\eta_c \to K^0_S K^- \pi^+$ and $\eta_c \to K^+ K^- \pi^0$ modes only. The $\eta_c \to K^0_S K^- \pi^+$ mode is the most precisely and reliably measured mode, while the branching fraction for the $\eta_c \to K^+ K^- \pi^0$ mode is related by isospin. The results are consistent with the CLEO results [16] but more precise as shown in Table 3.

Experiment	$\mathcal{B}(B^0 \to \eta_c K^0)$ $(\times 10^{-3})$	$\mathcal{B}(B^+ \to \eta_c K^+)$ $(\times 10^{-3})$
CLEO	$1.09^{+0.55}_{-0.42} \pm 0.12 \pm 0.31$	$0.69^{+0.26}_{-0.21} \pm 0.08 \pm 0.20$
BaBar	$1.06 \pm 0.28 \pm 0.11 \pm 0.33$	$1.50 \pm 0.19 \pm 0.15 \pm 0.46$
Belle	$1.23 \pm 0.23^{+0.12}_{-0.16} \pm 0.38$	$1.25 \pm 0.14^{+0.10}_{-0.12} \pm 0.38$

Table 3: The measured branching fractions for $B^+ \to \eta_c K^+$ and $B^0 \to \eta_c K^0$. The last errors come from the uncertainty in the η_c branching fraction

Belle has observed the decay mode $B^0 \to \eta_c K^{*0}$ for the first time. The K^{*0} is reconstructed in the $K^-\pi^+$ channel and the η_c in the $K^0_S K^- \pi^+$ mode. To remove the $B\overline{B}$ background, we apply vetoes to events consistent with $J/\psi \to K^0_S K\pi$, $\chi_{c1} \to K^0_S K\pi$ and $D_s \to K^+K^-\pi$. A fit to the M_{bc} spectrum yields a signal of 33.7 ± 6.7 events with a statistical significance of 7.7σ. The branching fraction for $B^0 \to \eta_c K^{*0}$ is found to be $(1.62 \pm 0.32^{+0.24}_{-0.34} \pm 0.50) \times 10^{-3}$. The ratio $R_{\eta_c} = \mathcal{B}(B^0 \to \eta_c K^{*0})/\mathcal{B}(B^0 \to$

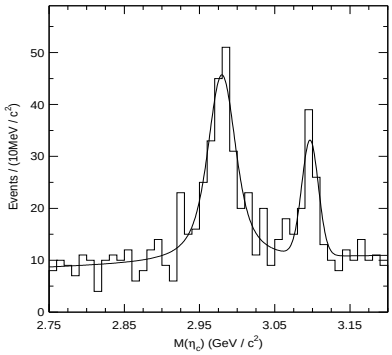

Figure 6: Candidate $M(\eta_c)$ invariant mass distribution for events in the M_{bc} and ΔE signal region. Signals at the η_c and J/ψ from $B \to \eta_c K$ and $B \to J/\psi K$ decays are visible.

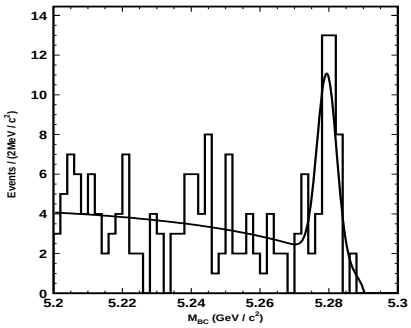

Figure 7: The M_{bc} distribution of $B^0 \to \eta_c K^{*0}$ candidates.

$\eta_c K^0$) is measured to be $1.33 \pm 0.36^{+0.29}_{-0.40}$. This result is somewhat higher than the theoretical prediction of Gourdin, Keum and Pham of 0.78 [17].

3.4 Exclusive $B \to J/\psi$, $\psi(2S)$ and χ_{c1}

Table 4 lists branching fractions for two-body B meson decays to J/ψ, $\psi(2S)$ and χ_{c1} with a kaon or pion [14] [18] [19] [20] [21] [22]. They are in good agreement with previous measurements but more precise. The decay modes $B^0 \to \chi_{c1} K^{*0}$, $B^+ \to J/\psi K_1^+(1270)$ and $B^0 \to J/\psi K_1^0(1270)$ have been observed for the first time.

Decay mode	Previous ($\times 10^{-4}$)	BaBar ($\times 10^{-4}$)	Belle ($\times 10^{-4}$)
$B^- \to J/\psi K^-$	10.0 ± 1.0	$10.1 \pm 0.3 \pm 0.5$	$10.1 \pm 0.3 \pm 0.8$
$B^0 \to J/\psi K^0$	9.6 ± 0.9	$8.3 \pm 0.4 \pm 0.5$	$7.7 \pm 0.4 \pm 0.7$
$B^- \to J/\psi K_1^-(1270)$			$18.0 \pm 3.4 \pm 3.9$
$B^0 \to J/\psi K_1^0(1270)$			$13.0 \pm 3.4 \pm 3.1$
$B^- \to \psi(2S) K^-$	5.8 ± 1.0	$6.4 \pm 0.5 \pm 0.8$	$6.7 \pm 0.6 \pm 0.7$ (a)
			$5.7 \pm 0.5 \pm 0.8$ (b)
$B^0 \to \psi(2S) K^0$	5.0 ± 1.3	$6.9 \pm 1.1 \pm 1.1$	$6.0 \pm 1.1 \pm 0.7$ (a)
			$7.2 \pm 1.1 \pm 1.1$ (b)
$B^- \to \chi_{c1} K^-$	10.0 ± 4.0	$7.5 \pm 0.8 \pm 0.8$	$6.1 \pm 0.6 \pm 0.6$
$B^0 \to \chi_{c1} K^0$	$3.9^{+1.9}_{-1.4}$	$5.4 \pm 1.4 \pm 1.1$	$3.1 \pm 0.9 \pm 0.4$
$B^0 \to \chi_{c1} K^{*0}$		$4.8 \pm 1.4 \pm 0.9$	
$B^- \to J/\psi \pi^-$	0.51 ± 0.15	0.39 ± 0.09	$0.52 \pm 0.07 \pm 0.07$
$B^0 \to J/\psi \pi^0$	$0.25^{+0.11}_{-0.09}$	$0.20 \pm 0.06 \pm 0.02$	$0.24 \pm 0.06 \pm 0.02$

Table 4: Measured branching fractions. (a) $\psi(2S) \to l^+ l^-$ (b) $\psi(2S) \to J/\psi \pi^+ \pi^-$.

4 Observation of $\eta_c(2S)$ meson

The $\eta_c(2S)$ meson has not been experimentally well established. The Crystal Ball group reported possible evidence for the $\eta_c(2S)$ meson with a mass of 3594 ± 5 MeV [23]. The result has not been confirmed by the subsequent experiments.

Using a data set that contains 44.1 million $B\overline{B}$ pairs, Belle has searched for the $\eta_c(2S)$ meson produced via the exclusive decays $B^+ \to \eta_c(2S) K^+$ and $B^0 \to \eta_c(2S) K^0$ where $\eta_c(2S) \to K_S K^- \pi^+$. To remove backgrounds from $B \to D(D_s)X$ and $B \to K^*(890)K$ decays, D, D_s and K^* vetoes are applied. The M_{bc} and ΔE distributions are plotted for twenty-five $M_{K_S K \pi}$ bins. Clear B meson signals are seen in the bins corresponding to the η_c and near the expected mass of the $\eta_c(2S)$. The signal yields extracted from the simultaneous fits to the M_{bc} and ΔE distributions are plotted in Fig. 8. A clear peak is seen around 3.65 GeV/c^2 and identified as $\eta_c(2S)$. The distribution is fit to two Breit-Wigner functions for the η_c and $\eta_c(2S)$ respectively, a Gaussian for the J/ψ, and a second-order polynomial for the non-resonant contribution. These functions are convolved with a Gaussian resolution function determined from MC. The fit value for the mass is $3654 \pm 6 \pm 8$ MeV/c^2. The 90% confidence level upper limit for the intrinc width is 55 MeV/c^2. The results are consistent with expectations of heavy-quark potential models. The ratio of product

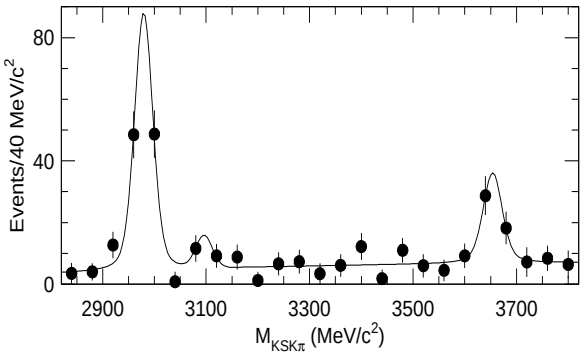

Figure 8: The signal yields for each $K_S K\pi$ bin. The curve is the result of the fit.

branching fractions for the η_c and $\eta_c(2S)$ is also measured to be

$$\frac{\mathcal{B}(B \to \eta_c(2S)K)\mathcal{B}(\eta_c(2S) \to K_S K^- \pi^+)}{\mathcal{B}(B \to \eta_c K)\mathcal{B}(\eta_c \to K_S K^- \pi^+)} = 0.38 \pm 0.12 \pm 0.05.$$

5 Summary

With the large $B\overline{B}$ data sets accumulated at the B-factories, we have improved the measurements of the branching fractions for the decays $B \to J/\psi K^{(*)}$, $B \to \psi(2S)K$, $B \to \chi_{c1}K$ and $B \to J/\psi\pi$. The decays modes $B^0 \to \chi_{c1}K^{*0}$, $B^+ \to \chi_{c0}K^+$, $B \to \chi_{c2}X$, $B^0 \to \eta_c K^{*0}$ and $B \to J/\psi K_1(1270)$ have been observed for the first time. The branching fractions for the non-factorizable decays $B^+ \to \chi_{c0}K^+$ and $B \to \chi_{c2}X$ are comparable to the factorizable decays $B^+ \to J/\psi K^+$ and $B \to \chi_{c1}X$. Belle has observed the $\eta_c(2S)$ meson. Its properties are consistent with expectations of the heavy-quark potential models.

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